UNITED VIRTUAL AIRLINES TRAINING DEPARTMENT

PILOT’S GUIDE

Aircraft Performance

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AIRCRAFT PERFORMANCE

1.- INTRODUCTION

There are four forces acting on an airplane: lift, weight (gravity), thrust and drag.

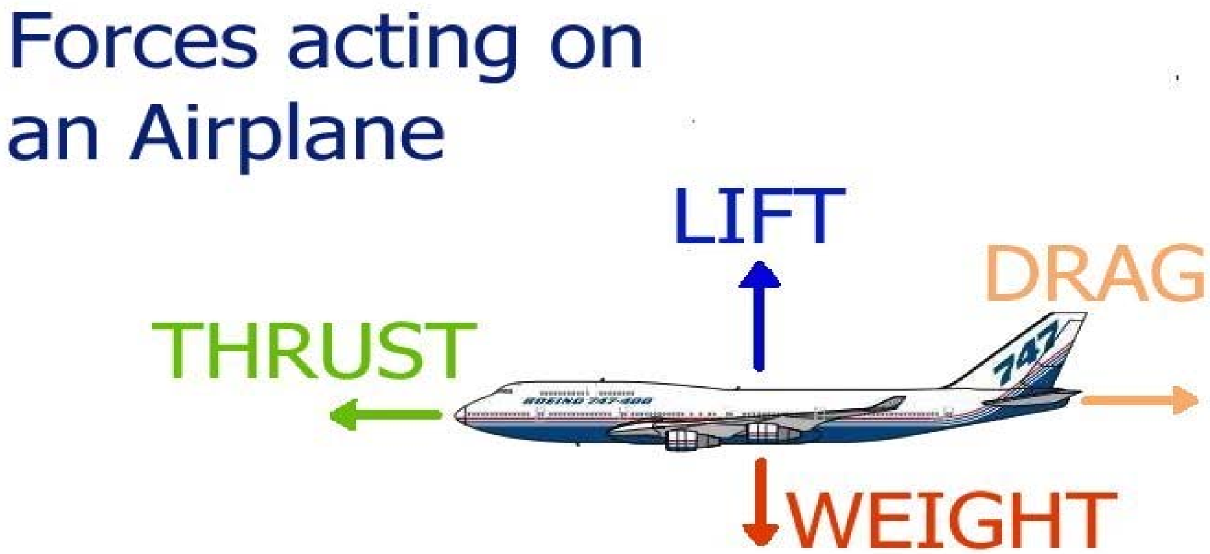

Fig. 1 – Forces acting on an airplane

Lift (L) is generated by the air flowing on the "lifting surfaces" (wings mainly, but also, to a much lesser extent, fuselage and stabilizer) and is a function of the "condition" of the air (ρ = air density), of the shape (C_L = coefficient of lift) and of the area of the lifting surface and (A) of the speed of motion through the air (V):

$$L = \tfrac{1}{2}\,\rho\,V^2\,C_L\;A$$

Using SI units, lift, being a force, is expressed in Newtons (N), with density in kg/m^3, speed in m/s and area in m^2.
The airflow around an airfoil creates a lower pressure (with respect to the undisturbed static pressure of the air) on the upper side of the airfoil and a higher pressure on the lower side.
The layer in the immediate vicinity of the surface of the airfoil is called the "boundary layer" and is where the viscosity is dominant and the majority of drag is created. The flow within the boundary layer is called "laminar" when the air flows in parallel layers and "turbulent" when the layers intermix and vortices generate. As the boundary layer thickens, it will transition from laminar to turbulent ("boundary layer transition"). In fluidodynamics, the ratio between inertial and viscous forces is called the "Reynolds number" (a dimensionless number). A low Reynolds number means that viscous forces are predominant hence the flow is more "ordinate" (laminar) while a high Reynolds number means that inertial forces are greater, hence the flow is dominated by eddies and vortices. Airliners tend to have high Reynolds numbers, so aerodynamicists do their best with the airfoil profiles to maintain a laminar flow for the greatest part of the airfoil, usually moving aft the thickest point (the so called "supercritical airfoils").
Lift distribution on the wing depends also on the form of the wing itself.

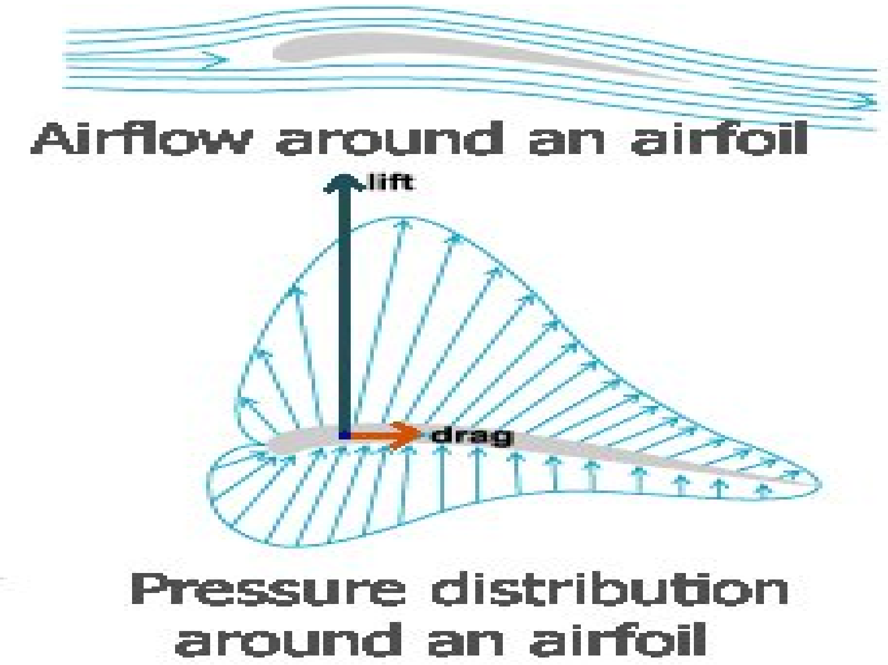

Fig. 2 – Airflow and pressure distribution around an airfoil

The coefficient of lift is not a constant, it depends on the type of flow over it which in turn is a function of the “shape” of the airfoil. A greater “curvature”, technically “camber”, gives a greater lift coefficient. The greater the angle of attack, the greater the coefficient, until a maximum after which a stall condition occurs, and the coefficient abruptly decreases.

Increasing lift in the critical phases of takeoff and landing means lower required speeds hence shorter runways. The “high-lift devices” either on the leading or the trailing edges of the wings increase lift by increasing the lift coefficient with a greater camber of the airfoil or by “energizing” the boundary layer thus retarding the boundary layer transition and/or increasing the wing surface.
The leading edge devices are called “slats” and come in 3 types: the Krueger flap (also called “droop”, a hinged flap which increases camber and area), the leading edge slat (a moving slotted flap which increases camber and area and energizes the boundary layer) and the fixed slat (a fixed slotted flap, used only in small STOL planes)
The trailing edge devices are called “flaps” and come in 4 types: the plain flap (hinged as an aileron), the split flap (in the lower part of the wing), the Fowler flap (which slides backwards and downwards), the slotted flap (a slot between the wing and the flap wing enables high pressure air from below the wing to re-energize the boundary layer over the flap). A typical Boeing solution is the slotted Fowler flap (triple slotted on the 747) which sums the effects of the Fowler and the slotted flap.

Drag (D) is generated by the friction of air flowing over the parts of the airplane. Total drag on an airplane in subsonic flight is the sum of parasite drag (itself the sum of friction and form or pressure drag), induced drag and interference drag.
Parasite drag is caused by the friction of the air particles against the surface of the aircraft (friction drang) and by the separation of air flowing on the surfaces of the airplane, which creates turbulence and results in pockets of low and high pressure that leave a wake behind the airplane or airfoil (form or pressure drag). Induced drag is created by the vortices at the tip of an aircraft's wing, hence is the drag due to lift, like a cost to be paid for generating lift: the high pressure underneath the wing causes the airflow at the tips of the wings to curl around from bottom to top in a circular motion and this results in a trailing vortex. Interference drag arises from the complex effects on airflow when the components of an aircraft are combined together, hence the drag of one component can affect the drag associated with another component. However, in a few instances, the combination of two

elements (e.g: the wing and the winglet) gives a total drag which is actually less than the sum of the two components' drag.

Drag may be represented by the following formula, which is identical to the lift formula. D, being drag, is affected by the same factors: "condition" of the air (air density), shape (C_D = coefficient of drag) and area of the surface (A) and the speed of motion through the air (V):

$$\mathbf{D = \tfrac{1}{2} \rho V^2 C_D\ A}$$

Using SI units, drag, as lift, is expressed in Newtons.

Lift and Drag coefficients are both a function of the airfoil shape and of the angle of attack.

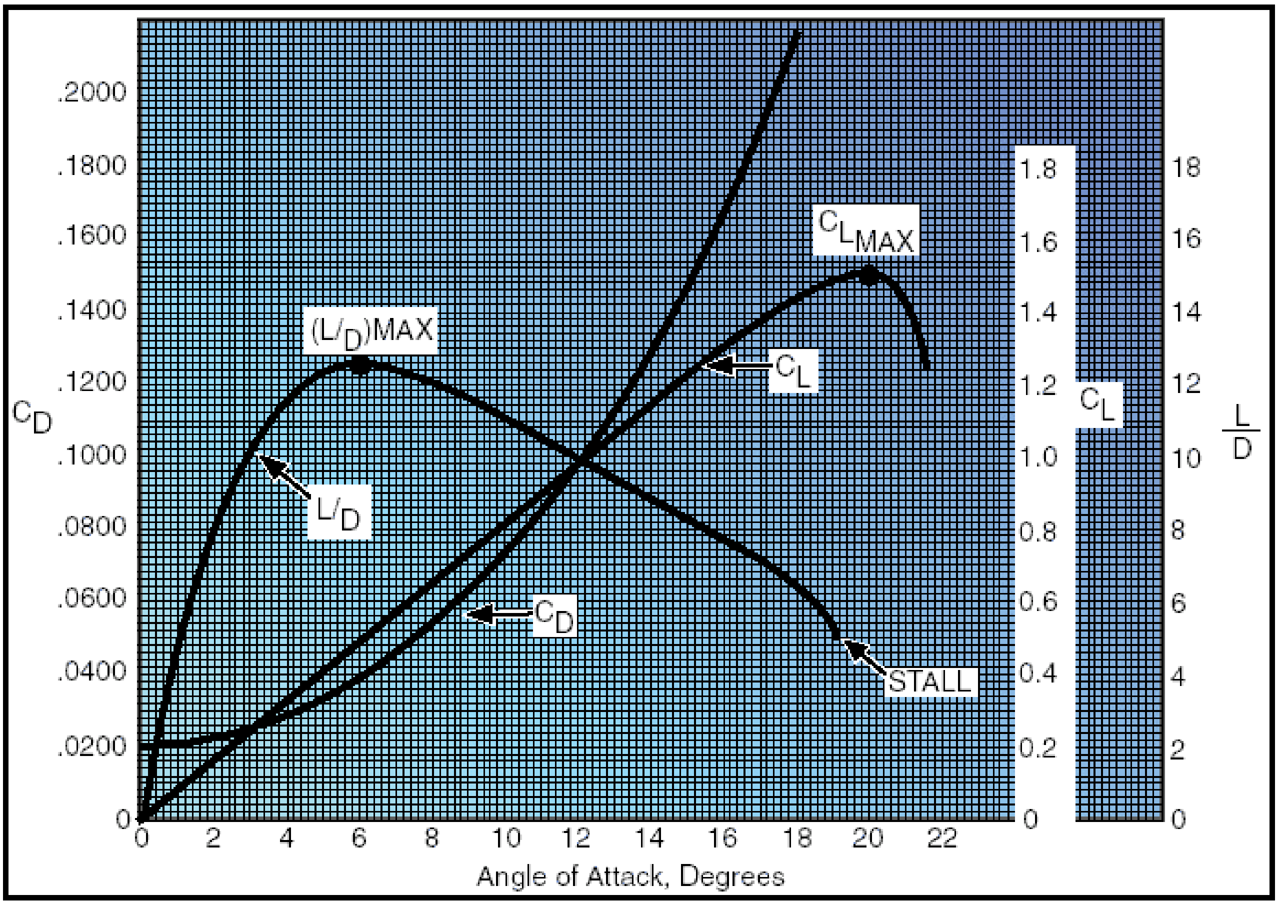

Fig. 3 – Lift and Drag coefficients (and the ratio of L to D) as a function of the AoA

2.- CLIMB AND MANEUVERING PERFORMANCE

When lift equals weight and thrust equals drag, the airplane is in straight and level flight.
In a climb, the forces "forward" (thrust) must be equal to the forces "aft" (drag and the component of weight which "pulls" aft):

$$T = D + W \sin \gamma$$

Where:
T = thrust
D = drag
W = weight
γ = angle of attack (angle between flight path and the horizontal)

From the above formula, it's clear that angle of attack is proportional to the "thrust excess" (T less D).

The rate of climb (ROC) is described by the following formula:

$$ROC = 101.3\ V \sin \gamma = 101.3\ V\ [(T-D) / W]$$

Where:
ROC = rate of climb in fpm
V = true airspeed in kts
T, D, W = thrust, drag and weight in lbs

In a steady and coordinated *turn*:

$$n = L / W = 1 / \cos \varphi$$

Where:
n = load factor
L = lift
W = weight
φ = bank angle

The rate of turn (ROT) in degrees per second is:

$$ROT = (1091 \tan \varphi) / V$$

Where:
V = true airspeed in knots
At the standard rate of turn (3°/s), the required bank angle is: 26° at 180 kts, 30° at 210 kts, 34° at 250 kts.

Turn radius (TR, in feet) is given by:

$$TR = V^2 / (11.26 \tan \varphi)$$

3.- TAKEOFF AND LANDING PERFORMANCE

Takeoff and landing performance are a function of:
- Aircraft and high lift devices design
- Engine performance
- Ambient conditions
- Weight
- Wheels performance

- Runway condition

High lift devices will help in generating more lift (and, in case of landing, also more drag) without requiring excessive speeds or attitudes.
Engine performance will be affected by ambient conditions (see below).
Ambient conditions (especially altitude, temperature and wind) will affect lift and engine performance (see below).
Aircraft weight will affect the amount of lift, and hence the thrust, required.
Wheels performance (inflating pressure, tyre shape, brake effectiveness) and runway condition (smooth, rough, grooved, dry, wet, contaminated or iced) will affect the rolling friction.

The required amount of runway for takeoff (and for landing) will depend on the aircraft total acceleration (deceleration, that is, negative acceleration, for landing). Assuming a uniform acceleration (which is approximately true for landing, not so much for takeoff), the required distance to bring an aircraft from zero to takeoff (Vr) speed or from landing speed (Vref) to a full stop, is given by:

$$\mathbf{S = V^2 / 2\,a}$$

Where:

S= takeoff or landing distance (feet)
V = Vr or Vref (ft/s)
a = acceleration (ft/s^2)

The total acceleration depends on the net forces acting on the airplane (lift, drag, thrust, friction) and the weight of the airplane:

$$\mathbf{a = g\,Fn / W}$$

Where:
g = acceleration of gravity
Fn = net forces acting on the airplane
W = weight

Usual values of a are around 0.2 g (about 6 ft/s^2) for both takeoff and landing.
So, the primary factors affecting takeoff and landing distances are speed and acceleration, both of which are a function of weight.
Calculating the required takeoff and landing distance (that is, the required runway to takeoff and to reach an altitude of 35 ft and the required distance to land and stop from an altitude of 35 ft), however, is a complicated matter, which takes into account the variable acceleration during the rolling, maneuvering (rotation and flare) and flight phases. These different (and variable) acceleration take into account not only engine and aircraft performance (affected also by ambient conditions), but include brake effectiveness and timing (and availability of autobraking), use of spoilers and reverse thrust, wheels performance and runway condition.

4.- EFFECTS OF ALTITUDE AND TEMPERATURE ON TAKEOFF AND LANDING PERFORMANCE

The air density plays a paramount role in both lift and drag.
All other conditions held constant, a low air density will generate less lift.
This means that an aircraft will need more speed to achieve the same amount of lift, hence more thrust and hence more runway to attain that higher speed.

The air density decreases when:

- *Temperature increases* (hot air is less dense than cold air)
- *Altitude increases*

- *Humidity increases* (this may seem contrary to logic, but the molecular mass of water is about 40 % less than the average molecular mass of air and, since a volume of gas at a given temperature and pressure, always contains the same number of molecules – Avogadro's law – when a number of water vapor molecules are introduced into a volume of air, the number of air molecules must decrease by the same value, hence the mass per unit volume, its density, decreases)

A lower density will produce negative effects on:

- Lift
- Power (less density means less oxygen intake)
- Propeller efficiency on prop planes (the propeller is a small wing, so the negative effects on lift are the same here)

The negative effects will translate in:

- Slower acceleration on the runway due to the decreased power available
- Higher takeoff speeds
- Longer takeoff runs
- Reduced climb rates
- Reduced service ceilings

In turn, a lower density will produce a positive (but very small) effect on drag, which however will be more than offset by the increase due to increased speeds to attain the same lift.

Density altitude is the altitude in the International Standard Atmosphere (ISA) at which the air density would be equal to the actual air density at the place of observation. In other words, the altitude at which the airplane "thinks" it is. Density altitude may be calculated in several ways:

- Using the following formula:

  (Dry) density altitude (feet) = 144745.12 x {1 - [(P_0 / P_{SL}) / (T / T_{SL})]^b}

  Where
  P_0 = actual atmospheric pressure in Pa
  P_{SL}= standard sea level pressure in Pa (101325 Pa)
  T = actual temperature in K (K = °C + 273.15)
  T_{SL}= standard sea level temperature in K (288.15 K)
  b = 0.235

- Using the following simplified formula (results will be approximate):

  Density altitude (feet) ≈ Pressure altitude + 120 x (SAT – T_{ISA})

  Where
  SAT = Static Air Temperature in °C
  T_{ISA} = Temperature at the actual elevation according to ISA in °C (T_{ISA} = 15 – 0.00198 x Elevation in feet)

- Using an aviation computer or a web-based calculator

- Using a density altitude chart (eg. Fig. 4)

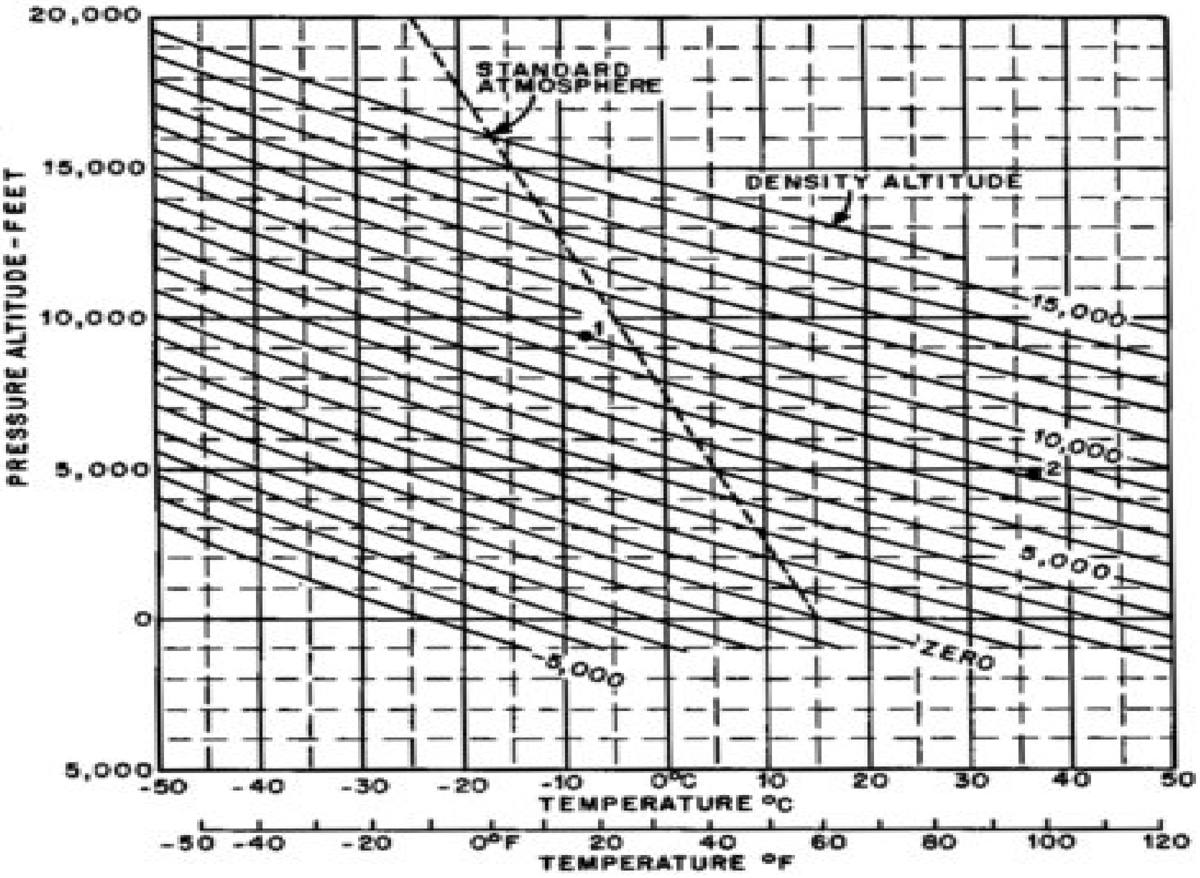

Fig. 4 – Density Altitude Computation Chart

Computation of the density altitude is of paramount importance, especially in a "hot and high" environment. Performance deterioration due to density altitude may require weight (payload and/or fuel) reduction or prevent a derated thrust takeoff. In the case of fuel limitations (to avoid payload "offloading"), careful planning must be considered and additional enroute refueling stops might be required. To enhance performance, it may be advisable to use higher flaps settings (i.e: Boeing 757/767 flaps 15 instead of 5). Rolling takeoffs should be avoided. Runway length requirements must be careful considered and accelerate/stop distance must be calculated especially at higher weights and with contaminated runways.

5.- EFFECTS OF WIND ON TAKEOFF AND LANDING PERFORMANCE

The effect on wind on takeoff and landing distances is given by the following formula:

$$\mathbf{S_W = S_{zerowind} \left[1 - (V_{hw} / V_r) \right]^2}$$

Where:

S_W = takeoff (landing) distance in actual wind conditions
$S_{zerowind}$ = takeoff (landing) distance in zero wind conditions
V_{hw} = wind velocity (headwind component; a tailwind component will have negative values)
V_r = takeoff (landing) reference speed in zero wind conditions (Vr or Vref)

For example, if we assume a headwind component which is 10 percent of the takeoff Vr (say, 13 kts for a typical Vr of 130 kts), the distance required for takeoff will be 81 % (a 19 % reduction) of the one required in zero wind conditions.
Taking off with a tailwind will translate in a greater penalty: a tailwind of 10 percent of Vr will increase the required takeoff distance by 21 percent compared with the zero wind requirement. This is why "takeoff and land into the wind" is an old aviation rule.